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A Comparison of Near-Infrared Spectroscopy and Reflectance Sensors to Traditional Pulse Oximetry Under Conditions of Low Blood Oxygen Saturation

Although the Navy has made substantial investments in aviation safety training to mitigate risks associated with hypoxia, the number of reported incidents continues to rise. In response to hypoxia's impact on flight safety, the Navy has identified the need for an oxygen warning and monitoring system as one of its primary aircrew system requirements. Rapid depressurization events are easily recognized, but most hypoxia-related incidents involve moderate hypoxia, such as following the malfunction of an oxygen delivery system. Currently there are no means to monitor the physiological or cognitive status of aircrew in any military aircraft. Survival requires pilots and aircrew to recognize that a hypoxic event is occurring while they have enough cognitive reserve to enact the correct emergency procedures. Pilots then rely on their personal judgment to determine when they have recovered sufficiently to land or perform other difficult maneuvers. This approach may pose risks given that hypoxia exposure is known to significantly impair judgment and decision making, placing pilots at risk immediately following a significant hypoxic event.

One potential solution to this problem would be the deployment of a reliable hypoxia detection and warning system capable of sensing hypoxia in its early stages. Aircrew could be alerted with sufficient time to initiate countermeasures before their performance is significantly degraded. However, several major technical challenges must be overcome to develop a detection and warning system that functions accurately and consistently in the dynamic environments commonly found in military aviation. The system must provide accurate and continuous monitoring of blood oxygen levels in motion environments without generating spurious readings. The system must also be highly responsive to sudden drops in blood oxygen saturation and predictive of pilot and aircrew performance. Additionally, the system must provide accurate measurements when individuals possess blood oxygen saturation values significantly below those experienced in clinical settings (e.g. below 70%).

In light of these challenges, investigators at the Naval Aerospace Medical Research Laboratory (NAMRL) have completed two experiments comparing the performance of four off-the-shelf oxygen saturation monitoring technologies: Near-infrared spectroscopy, reflectance oximetry, and finger and ear pulse oximetry. Both experiments were designed to directly compare the accuracy and sensitivity of these more central measurements of blood oxygen saturation with traditional finger pulse oximetry in detecting dramatic drops in blood oxygen saturation, as well as, the potential for their use in military aviation platforms. In experiment one, a forehead-mounted reflectance oximeter was compared to a finger pulse oximeter for



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accuracy, agreement, and sensitivity. Subjects were given a gas mixture (oxygen/nitrogen) equivalent to an altitude of 18,000 feet for a period of 30 minutes followed by a 10 minute sea level equivalent recovery period. Results suggest that the forehead oximeter responds faster than the finger oximeter to sudden drops in blood oxygen saturation. Unfortunately, despite superior responsiveness when compared to the finger, the forehead-mounted oximeter was especially susceptible to dropped data points resulting from slight head movements, which limits the system's utility in extreme motion environments.

In experiment two, subjects were equipped with a finger pulse oximeter, an ear pulse oximeter, and a forehead-mounted near-infrared spectroscopy (NIRS) sensor designed to measure regional blood oxygen saturation in the cerebral cortex. Subjects were given a gas mixture equivalent to 20,000 feet for a period of 10 minutes followed by a 10 minute sea level equivalent recovery period. Subjects performed one minute blocks of the Flanker Arrow Task, a cognitive test of executive function, followed by one minute rest periods between blocks throughout the exposure and recovery profile. Results showed that both the NIRS sensor and the ear oximeter responded significantly faster to sudden drops in blood oxygen saturation than the finger oximeter. Like the forehead-mounted reflectance oximeter evaluated in experiment one, the ear oximeter returned a large number of dropped data points in the presence of slight motion. Conversely, the NIRS sensor provided continuous monitoring throughout the protocol without motion induced interruptions to data acquisition. The NIRS system also appeared more compatible with subjects' cognitive performance during recovery from hypoxia. According to the finger and ear oximeters, arterial blood oxygen saturation was restored to pre-exposure values approximately 90 seconds after subjects were given a sea level equivalent air mixture. Conversely, both NIRS readings and cognitive performance failed to return to pre-exposure levels during the 10 minute recovery. This may suggest that NIRS provides a more accurate indication of an aircrew member's functional state following hypoxia exposure than traditional oximeters.

These studies suggest that both the forehead-mounted reflectance oximeter and ear oximeter picked up on desaturation events significantly faster than the finger oximeter while maintaining a high degree of accuracy. Unfortunately, both of these technologies are highly susceptible to dropped data points in the presence of motion. The vulnerability to motion artifacts limits the utility of the forehead-mounted reflectance oximeter and ear oximeters in aviation settings where extreme motion is common. A high frequency of dropped or spurious data points would result in the interruption of continuous monitoring and potentially trigger false alarms, undermining pilot trust in, and responsiveness to, the hypoxia warning system. This research suggests that NIRS is more sensitive to sudden drops in oxygen saturation associated with exposure to acute hypoxic stress than both the finger and ear oximeters. In addition, NIRS readings appear to possess a stronger association with a subject's cognitive state during recovery from hypoxia than traditional pulse oximetry methods. This may imply that the NIRS system provides a more accurate picture of the functional state of aircrew following a hypoxia event. NIRS systems have also been shown to deliver accurate and continuous monitoring in studies using high-G centrifuges. The sensor was not susceptible to dropped or spurious data points during the on-set of rapid accelerations and other extreme motion experienced during testing. NIRS's superior sensitivity and resistance to motion artifacts suggest it may be better suited than pulse oximetry for early detection of hypoxia in military aircraft. More laboratory work, and eventually field studies, must be done to establish the validity of these findings. More work must also be done to confirm that NIRS oxygen saturation measurements following hypoxia exposure are indicative of a compromised functional state and not simply a spurious result. For now, however, these studies point in a promising new direction for hypoxia detection and early warning research and development.

REPORT DOCUMENTATION PAGE

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14. ABSTRACT Although the Navy has made substantial investments to mitigate risks associated with hypoxia, there are currently no means to monitor the physiological or cognitive status of aircrew in any military aircraft. One potential solution to this problem would be the deployment of a physiological monitoring and warning system. NAMRL investigators have completed two experiments comparing the performance of four oxygen saturation monitoring technologies: Near-infrared spectroscopy (NIRS), reflectance oximetry, and finger and ear pulse oximetry. In experiment one, a forehead-mounted reflectance oximeter was compared to a finger pulse oximeter during exposure to a simulated altitude of 18,000 feet. Results suggest that the forehead oximeter responds faster than the finger oximeter to sudden drops in blood oxygen saturation. Unfortunately the forehead-mounted oximeter was especially susceptible to dropped data points resulting from motion. In experiment two, subjects were equipped with a finger pulse oximeter, an ear pulse oximeter, and a forehead-mounted NIRS sensor during exposure to a simulated hypoxia profile including an altitude of 20,000 feet and a recovery phase. Subjects performed a cognitive test throughout the profile. Results showed that both the NIRS sensor and the ear oximeter responded significantly faster than the finger oximeter, although the ear oximeter returned dropped data points in the presence of motion. Conversely, the NIRS sensor provided continuous monitoring throughout the protocol and appeared more compatible with subjects' cognitive performance during recovery from hypoxia. Overall, the results imply that the NIRS system provides an accurate picture of the functional state of aircrew following a hypoxia event. NIRS's superior sensitivity and resistance to motion artifacts suggest it may be better suited than pulse oximetry for early detection of hypoxia in military aircraft. More work must be done to establish the validity of these findings.					
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